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Formation of desert pavements and the interpretation of lithic-strewn landscapes of the central Sahara

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ABSTRACT

This study focuses on two different but interlinked lines of evidence that critically examine land surface processes contributing to the formation of desert pavements in the central Sahara. (1) Soil pedostratigraphies from the Messak plateau (SW Libya) illustrate phases of land surface stability and instability that reflect humid and arid phases of Quaternary climate, respectively. (2) The density and morphologies of surface lithic scatters in the same region were re-examined, based on data previously published by Foley and Lahr (2015, PLoS ONE). This re-examination shows that many surface clasts previously interpreted as lithics are better interpreted as formed by *in situ* weathering and wind abrasion. Furthermore, weathering, abrasion and deflation are the major processes by which desert clasts are formed and concentrated on the land surface, not human agency. Erosional Quaternary periods allowed for the formation of condensed pedostratigraphies by which surface clasts and lithics were mixed and concentrated on the land surface. These two independent lines of evidence show that desert land surfaces do not reflect a single time period of formation, and that Quaternary desert pavements (including any lithics located thereon) evolved in response to subaerial weathering and erosion processes.

1. Introduction

Geomorphological processes are particularly active in regions that experience extreme climatic regimes and relatively rapid climate changes, including the central Sahara. Climate-driven weathering and subsequent sediment transport in this region throughout the Cenozoic has resulted in the formation of extensive weathered bedrock surfaces, on which small grain sizes have been lost by deflation or transported by episodic flash floods, leaving a hamada-like mantle of surficial clasts mainly of pebble and boulder sizes (Zerboni, 2008; Adelsberger and Smith, 2009; Zerboni et al., 2011; Fookes et al., 2013). Variations in aridity/humidity throughout the Quaternary, in particular, have resulted in episodic landslides (Busche, 2001; Lee et al., 2013), river/lake development (Cremaschi, 2001; Drake et al., 2008), ecosystem changes (Parker et al., 2008; Cremaschi et al., 2014), and responses to these changing conditions by human activity (Geyh and Thiedig, 2008; Mercuri, 2008; Cremaschi and Zerboni, 2009). One of the less considered effects of wet to dry Quaternary climatic transitions in desert regions is the weathering of exposed rocks and the formation of soils during wet periods, and their breakup and erosion as a consequence of enhanced wind activity in glacial/arid times. The main effect of the interplay between dust input, soil forming processes, and deflation is the formation of desert stone pavements (e.g., Watson and Nash, 1997; McFadden et al., 1998; Dietze et al., 2013; Goudie, 2013; Fuchs et al., 2015). The final stage in formation of a desert pavement is the creation of a layer of clasts, generally covered by a dark rock varnish and/or polished by wind. These clasts become embedded within the finer matrix of the topsoil, where present. According to the time of development of the surface, more than one clast layer or palaeosol can be found in the stratigraphy, buried by aeolian or colluvial sediments (Fuchs et al., 2015). Moreover, human groups extensively settled in deserts such as the Sahara, in particular during wetter interglacial phases of the Pleistocene (Jones and Brian, 2016), leaving behind them an impressive quantity of stone tools and débitage. The latter, especially those dating to the Pleistocene, can become part of the desert pavement surface. Key evidence for prehistoric human activity in the central Sahara region is therefore the presence of surficial lithic scatters (Adelsberger et al., 2013; Foley and Lahr, 2015). Lithics are defined as anthropogenically-formed stone materials, including stone tools and débitage. Lithics are a subset of all clasts present on the land surface, which mostly include clasts that have not been shaped by human activity but by subaerial weathering. The terms *lithics* and *clasts* are used herein according to these specific definitions.

Although many studies have been concerned with the Holocene

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archaeology and cultural anthropology of the central Sahara, particularly in the central Sahara (e.g., Cremaschi and di Lernia, 1998; Cremaschi and Zerboni, 2009; di Lernia et al., 2013; Cremaschi et al., 2014; Guagnin, 2014), fewer studies have examined the archaeology of earlier time periods across the region (e.g., Cancellieri and di Lernia, 2013; Drake et al., 2013; Cremaschi et al., 2014).

A recent study by Foley and Lahr (2015) presented evidence for high-density lithic scatters, based on observations from 50 randomly-sampled 1 x 1-m quadrats, from across the surface of a very small portion of the Messak plateau (SW Libya). Based on simple counting of the number of lithics from within these quadrats, Foley and Lahr calculated lithic density (expressed as number of lithics/m^2), and then extrapolated this figure across the wider region that had been previously surveyed (some > 400 km^2). They calculated an average density of 75 lithics/m^2 and thus 7.5×10^7 lithics/km^2 across the region as a whole which, they argued, is consistent with a 'modelled' value based on population density, length of time of occupation, number of flakes used, débitage production, and tool volume. However, they did not consider the geomorphological processes shaping the land surface in such an arid region, in the interpretation of this evidence.

In this paper, we revisit the relationship between geomorphological and anthropogenic processes in the morphology and concentration of clasts on desert pavements in the central Sahara. This paper (i) defines the main natural surface processes responsible for the formation of desert pavements based on published and new evidence from the Messak plateau region of southwest Libya, including soil pedosequences, and (ii) critically re-examines the methodology and results obtained, and the interpretation of the results, from this region by Foley and Lahr (2015), in the light of this new evidence and with reference to what is already known about the formation of desert pavements. Thus, our study sets the reanalysis of these previous data into a wider climatic, geomorphic and environmental context. This critical re-examination is needed because, in order to evaluate the formation of desert pavements, one must consider (i) the physical weathering and erosion processes that can substantially modify the morphology of any surface clasts, and (ii) the nature of macroscale landscape evolution over long time scales (< 500,000 years) which may substantially impact on the density of lithics recorded on the surface today, as well as the density of clasts in total.

In detail, this paper (1) outlines the geology and geomorphology of the Messak plateau; and (2) presents new field evidence for the complex processes forming desert pavements in the region. (3) We then consider the data presented in Foley and Lahr's (2015) study, and re-calculate lithic density based on excluding those clasts which have been formed by natural – not anthropogenic – processes. (4) We then show that macroscale landscape evolution by deep and surface weathering, and subsequent deflation, can form a condensed stratigraphy which concentrates clasts (and any lithics) on the surface, which casts doubt on the value of calculations of lithic density. These geomorphological considerations are important if one is to accurately consider the impacts of past human activity on the regional landscape, and thus the wider context of the 'Palaeoanthropocene' of the central Sahara.

2. Geology, geomorphology and climate of the Messak plateau

The Messak plateau (~15,000 km^2) is a prominent topographic feature of the north-central Sahara, in SW Libya (Fig. 1). This plateau consists of two separate units (the Messak Settafet and the Messak Mellet) and is underlain by massive, east-dipping Cretaceous (Nubian) sandstones, which are occasionally interbedded with thinly-bedded shales and conglomerates (Cremaschi, 1998; El-Ghali, 2005). The western and northern edges of the plateau form a steep (300 m high) scarp in the Messak Mellet, which reaches maximum altitudes of ~1200 m asl. The remainder of the plateau dips shallowly (< 1°) eastwards, where the plateau contains evidence for both wholly relict and some contemporary landscape elements. Relict features include low-relief bedrock surfaces with high-density and relatively large blocky debris (hamadas) or with smaller rounded debris (serir); bedrock surfaces covered with patches of Neogene to Pleistocene rubified palaeosols (Zerboni et al., 2015a); a deeply incised dendritic fluvial network, today almost fossil, but in the Pleistocene able to form gravel mega-bars; a complex system of underground and surface solutional features (Perego et al., 2011); and Pleistocene fluvial terraces overlying bedrock surfaces in the lower-elevation east of the region (Perego et al., 2011; Zerboni et al., 2015a). The dendritic drainage system cutting the Messak plateau and forming stepped canyons probably evolved from the Tertiary (likely the Oligocene or Miocene), in response to wetter climate and regional uplift (Busche, 2010; Hounslow et al., 2017). After this initial phase, rivers were periodically reactivated during humid periods over millions of years, up to the early Holocene (Perego et al., 2011), contributing to removal of the pedogenic cover of the plateau. As a consequence, the headwater areas of most wadis have high denudation rates, exposing sandstone bedrock outcrops (Zerboni, 2008). Erosion in headwater areas can moreover be matched with alluvial megafans formed at plateau footslopes, as in the case of the Wadi Berjuj gravel-bearing alluvial fan (Perego et al., 2011). Parts of the ancestral regional drainage system and several gravel-bearing alluvial fans have been buried under dunes of the adjacent Murzuq sand sea (Perego et al., 2011). Significant regional land surface elements are shown in Fig. 2 and their distribution reported in the simplified geomorphological map (Fig. 1).

During the Quaternary, deep and thin paleosols formed on the Messak plateau, but these were partially or entirely removed by wind erosion during arid (glacial) phases (Trombino, 1998; Zerboni et al., 2011). However, this erosion or reworking was not spatially or temporally uniform. As a consequence, the surface of the plateau experienced differential accumulation of residual clasts that constitute the desert pavement (Fig. 2). The presence of a Mn-bearing rock varnish (Cremaschi, 1998; Zerboni, 2008) permits a remote sensing approach to define the occurrence of areas where surface stoniness and stability are highest (Zerboni, 2008; Zerboni et al., 2015a). The spectral band ratio 5/4 of Landsat TM and ETM + platforms provides a good index for varnished surfaces, giving the highest values where bare rock outcrops dominate. Holocene landscape elements include east-draining ephemeral wadi systems, which may include a mixture of fluvial gravels, aeolian reworked sands, shallow soils and Mn-bearing weathering surfaces. Isolated bedrock hilltops are also found across the plateau region and in association with all landscape elements. AMS-^{14}C dating has shown that rock varnish on surface boulders of the Messak plateau developed episodically throughout the Holocene in response to variations in humidity (Zerboni, 2008), and that black Mn-rich varnishes formed after the mid-Holocene climatic transition.

Climatically-driven weathering is the major control on the macroscale geomorphology of the northern and central Sahara regions (Wright, 2001; Zerboni, 2008; Perego et al., 2011). The major weathering processes are thermal heating and cooling on bare rock surfaces and boulders (Moores et al., 2008; Eppes et al., 2010; Dorn, 2011; Viles and Goudie, 2013); rare salt wedging and episodic freeze-thaw where moisture is present within rock fractures (Aref et al., 2002); and granular disintegration, which particularly affects sandstone (Labus and Bochen, 2012), the dominant lithology in this area. Mechanical abrasion by wind-blown sand also takes place, because of the availability of loose quartz sand and silt grains as weathering products (Wright, 2001), unstable and unvegetated land surfaces, and vigorous seasonal wind patterns, but its effects are hampered by surfaces affected by granular disintegration and mechanical weathering. These environmental conditions give rise to dust storms (Goudie and Middleton, 2001) and active sand dune migration (Al-Masrahy and Mountney, 2013). Associated with sediment transport is the formation of polished desert pavement surfaces (Zerboni, 2008; Adelsberger and Smith, 2009; Matmon et al., 2009), and boulder or rock surfaces with wind-abraded facets (ventifacts) (Wade, 1910; Desio, 1937; McCauley et al., 1980;

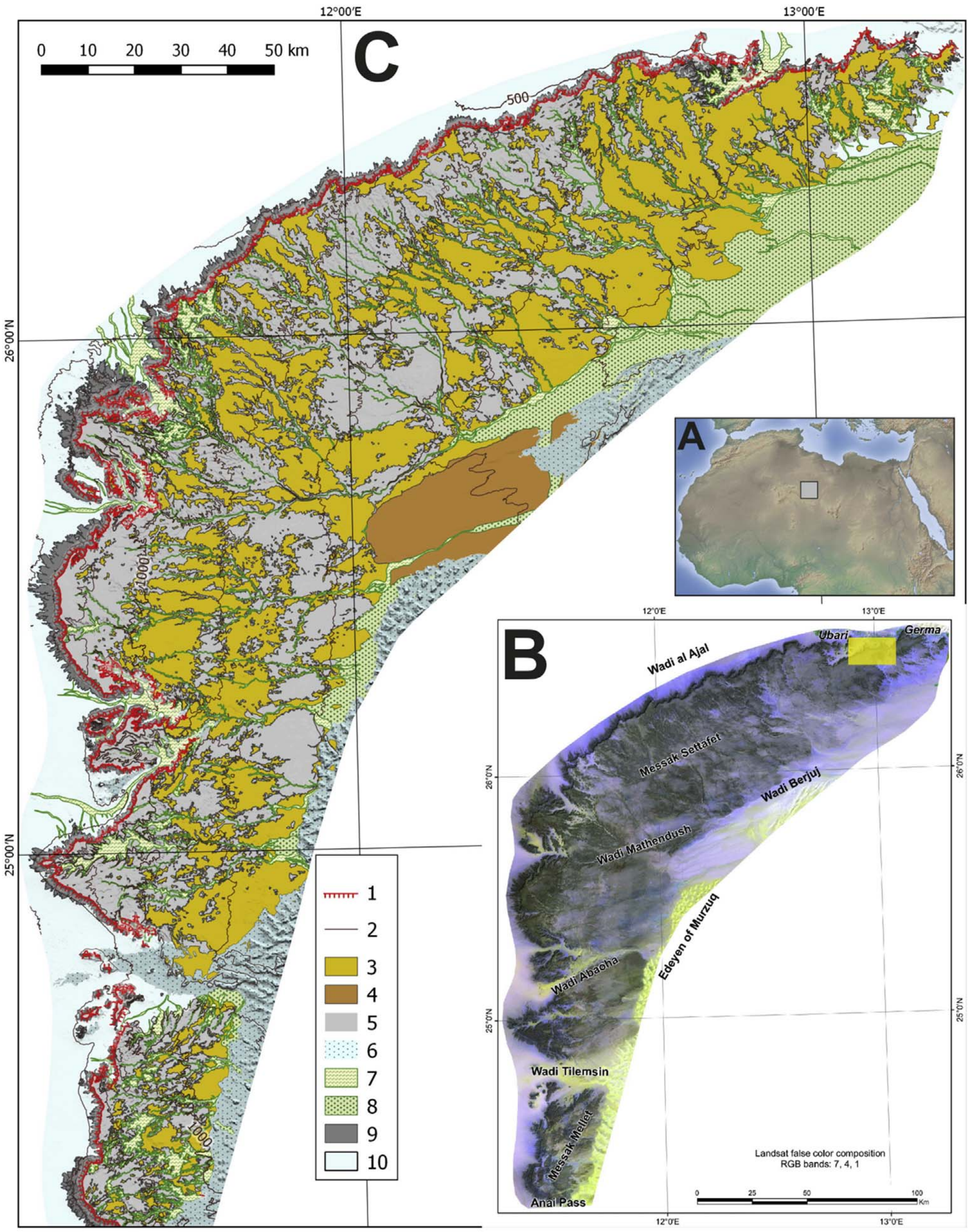

Fig. 1. (A) Position of the study region in North Africa. (B) Landsat satellite imagery of the Messak plateau; the yellow box on the main map indicates the location of the study region examined by Foley and Lahr (2015) in the northeastern part of the Messak Settafet. (C) Geomorphological map of the Messak plateau (simplified after Perego et al., 2011). Key: 1) escarpment; 2) contour lines; 3) residual desert pavement with rock outcrops; 4) latosol-related surfaces; 5) desert pavement (hamada or serir); 6) sand sheet and dunes; 7) wadi bottom with fluvial sediments; 8) Pleistocene fluvial sediments; 9) bare rock; 10) pediments. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Knight, 2008; Soleilhavoup, 2011). The presence of mobile sand dunes across the central Sahara region attests to sand movement under contemporary climatic conditions (Hereher, 2010; Salman et al., 2010), and it may be the case that such activity was invigorated as a result of regional changes in atmospheric circulation over the last 3–4 kyr (Swezey, 2001; Brookes, 2003). Recent work suggests the persistence of winds and dune activity for most of the Holocene, even during early and middle Holocene wet periods (Bristow and Armitage, 2016).

The present climate regime (2005–2014) near the Messak plateau at Ubari (26°34′59″N, 12°45′59″E; 463 m asl) and Ghat (25°6′30″N; 10°9′32″E; 693 m asl) gives mean summer (JJA) temperatures of 32 °C and 32.7 °C respectively, and mean winter (DJF) temperatures of 14.8 °C and 16.2 °C, respectively. January is the only month where frost days are recorded. Average wind speeds are 7.6 km h^{-1} (2.1 m s^{-1}) at Ubari and 11.6 km h^{-1} (3.2 m s^{-1}) at Ghat and winds are dominantly from the east and north, respectively (data from www.weatheronline.in). Total 3-month winter (summer) precipitation is 0.6 (0.2) mm at Ubari and 0.66 (0.40) mm at Ghat (data from www.weatherbase.com).

3. Methodology

This study considers the evolution of desert land surfaces and desert pavements on the Messak plateau, central Sahara, based on two complementary field and analytical approaches. The first is to consider the formation and development of soils and associated desert surfaces, based on field surveying and shallow excavation. The second is to consider the typology of clasts found on the land surface in this region, based on re-examination of previously-published quadrat data presented by Foley and Lahr (2015). The methodologies of these two approaches are now described in detail.

(1) Investigation of the formation and development of desert soils and surfaces is based on (i) field geomorphic mapping, reported in previous studies (Perego et al., 2011; Zerboni et al., 2011, 2015a), which identifies the distributions of hamada and serir surfaces. These studies also identify the generalised distributions of desert soils exposed at the surface; and (ii) examination of soils in the field which was based on pedostratigraphic logging and sampling within soil pits, dug from the surface to bedrock (30–100 cm deep) at selected sites across the

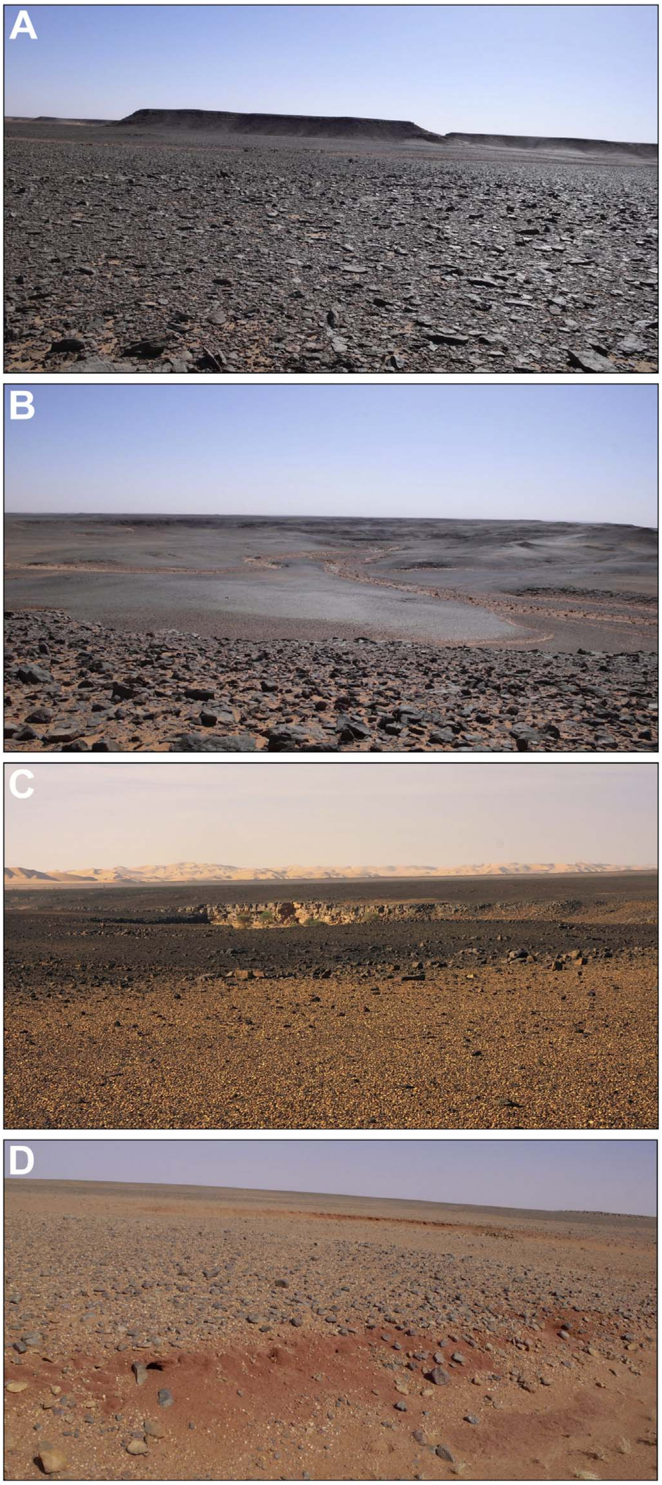

Fig. 2. Field photos of land surface features in the Messak plateau, showing (A) hamada of closely-packed angular clasts concentrated by deflation, with Mn-rich varnished clasts (and lithics) on the desert pavement; (B) wind-abraded clasts on hamada surface with intervening sediment patches located on exposed uplands (foreground) with relict fluvial channels downslope (background), on the southern fringe of the plateau (photo courtesy of M.E. Peroschi); (C) sandstone outcrop (middle ground) as a likely lithic source in the central Messak, obviating the need for surface quarrying, contrary to that argued by Foley and Lahr (2015) (photo courtesy of M.E. Peroschi); (D) surface lag of abraded clasts overlying residual red palaeosols beneath the hamada of the Messak Mellet (see model in Fig. 5). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

study area, informed by mapping studies (point i). In total 22 soil sites were investigated from across the Messak plateau, and their distributions well represent the many physiographic units present in the region; 15 soil sites are located along a transect crossing the central part of the massif (Zerboni et al., 2011), and 7 more soil sites are scattered mostly in the southern Messak region (Messak Mellet). A single soil profile considered here is located in the Tadrart Acacus massif (see Cremaschi et al., 2014) and it represents a good example of the Holocene formation of desert pavements. As local soils are the product of several phases of sediment accumulation and pedogenesis, we adopt the concepts proposed by Costantini and Priori (2007) to define pedostratigraphies and pedostratigraphic levels (i.e., horizons formed from parent materials having the same origin and age). Diagnostic B horizons of the soils, including buried B horizons, were defined according to the international classification systems proposed by WRB (2006) and Soil Survey Staff (2010). The application of this terminology is discussed by Zerboni et al. (2011, 2015b).

The methodological approach taken here to soil analysis and the relationship of soil development to desert surface formation is based on considering the interplay between sedimentary (erosion and deposition by wind and water) and pedogenic processes. Pedogenesis on the Messak plateau and surrounding regions is today almost inactive, and thus local surface soils can be regarded as paleosols despite the fact that they are not buried (relict paleosols, sensu Ruellan, 1971). The soils formed during several wet periods of the Quaternary and are the result of the superimposition of depositional and post-depositional processes that were able to progressively bury (or sometimes exhume) topographic surfaces (Zerboni et al., 2015a,b). Paleosols on the Messak are discontinuously preserved due to severe wind erosion, and the better-preserved areas of paleosols contain stone lines within their stratigraphies that correspond to older topographic surfaces not yet affected by wind erosion.

(2) Foley and Lahr (2015) in their supplementary data present photos of 12 examples (from their total of 50) of 1 m^2 quadrats from 5 different areas of the northern Messak plateau, from which they calculated the number of lithics per quadrat relative to the total number of clasts per quadrat. In this study, we have re-examined these 12 photos at high (x400) resolution, in order to confirm the numbers of individual lithics calculated by Foley and Lahr, and to identify those clasts that show surficial evidence for having been affected by one or more of the natural, physical weathering processes outlined above. Following Foley and Lahr's methodology, we consider all clasts over 2 cm in maximum dimensions. Given the resolution of the images provided by Foley and Lahr (2015) in their supplementary data, individual clasts approaching 2 cm in diameter are difficult to distinguish on the images, which is a limitation of our methodology. A second limitation is the impossibility to observe the buried part of each item; therefore our classification relies on the subaerially-exposed part of clasts and lithics only. However, surface features of larger clasts are shown clearly. To aid the classification of individual clasts, different clast surface features were identified. Particular attention was paid to the effects of physical weathering processes on clast surfaces. Within each quadrat, clasts showing these different surface morphologies were counted. Some clasts showing two distinctive morphologies were also counted and are included in the analysis.

The categories of surface features identified, and their genetic origins, are:

- Lithics (débitage flakes and formal stone tools). These are identified on the basis of multiple and intersecting fracture patterns, at different angles, across the clast surface, and sometimes the presence of retouching on clast edges. These clasts are of anthropogenic origin;
- Fractures. These are single or multiple planar surfaces that often form a sharp angle at clast edges; planar and smooth fracture planes often contrast with other clast surfaces that are rounded and irregular. Fractures most commonly result from thermal weathering

(thermoclastism), where a high diurnal temperature range causes minerals within the rock to expand and contract, causing brittle fracturing. Occasionally, fractures can be related to frost action, but in the central Sahara, where environmental humidity is very low, this process is not common;

- Polish. This results from the abrasive interaction of wind-blown sand grains with upstanding clast or bedrock surfaces, where these surfaces acquire a smooth, glossy sheen. Polish is most common on quartz-rich rocks, such as the fine sandstones and siltstones of the study area. Polished surfaces are smooth, rounded, and occasionally pitted. Pits also result from abrasion by wind-blown sand grains, particularly where there are mineralogical variations on the rock surface;
- Ventifacts. These are clasts whose surfaces have been shaped almost wholly by the abrasion of wind-blown sand. Here, high abrasion rates preferentially form intersecting smooth, planar to curved surfaces that reflect the direction of the prevailing wind (Knight, 2008). Common ventifact forms include a curved Brazil-nut shape and a triangle with three planar faces (known as dreikanter) (Kuenen, 1960);
- 'No diagnostic features'. Due to the resolution of the images, smaller clasts in particular often show no clear or diagnostic surface properties. As such, these were categorised as 'no diagnostic features', and are excluded from the analysis below. Clasts that show 'no diagnostic features' are often highly weathered by a range of subaerial processes in combination, and have a broken, knobbly surface texture.

4. Results

4.1. Desert soils and desert pavements

Mapping of desert soils and pavements on the Messak plateau shows that the extant pavement covers residual strips of paleosols. The latter are somewhat discontinuous, but they are more common and thicker towards the southern margin of the plateau, far from the main escarpment, and in the inter-wadi regions, where denudation processes are less intense (Perego et al., 2011). The main pedogenic processes described in the region includes rubification, clay translocation, and calcite redistribution, occurring since the late Pliocene/early Pleistocene on the sandstone bedrock, on fluvial deposits, and on wind-blown sediments (Trombino, 1998; Zerboni et al., 2011, 2015a).

These previous papers and this present study show a superimposed series of B horizons developed on different parent materials (pedostratigraphic levels). In many cases the stratigraphic boundary between two subsequent cycles of parent material deposition and pedogenesis is marked by the occurrence of an intraformational stone line, often including lithics. In Fig. 3, representative soil profiles published by Cremaschi (1998), Trombino (1998), Zerboni et al. (2011), and Cremaschi et al. (2014) are presented, including some unpublished soil profiles from this region, which are reported here for the first time, and are described in Table 1. Soil profiles vary locally across the Messak region, but we also considered two soil profiles (TK-WS and TR2) that were excavated on the flat stable surfaces of the Tadrart Acacus massif. This is located close to the Messak plateau and displays the same geological and paleoenvironmental contexts.

The soil pedosequences (Fig. 3) generally consist from top to bottom of (i) the surficial clast line of the hamada (or occasionally a pebble-strewn serir); (ii) a vesicular surface B horizon, occasionally showing platy aggregation; (iii) a transition marked by the accumulation of clasts or artefacts dating to the Holocene; (iv) a 2B horizon developed on an older parent material or on bedrock, sometimes enriched in clay (2Bt) or in calcium carbonate (2Bk); and (v) the bedrock surface, which is usually partially weathered (C or R horizon). These sequences can be complicated by the presence of a further 3B horizon, the upper limit of which can be again marked by a layer of clasts and Palaeolithic artefacts. As discussed by Cremaschi (1998), each of the transitions between the B and overlying horizons corresponds to a former topographic surface, apart from those cases where erosional surfaces are clearly visible.

In all profiles, and especially those from sites MT22 and TK-WS, we note the clear existence of buried topographic surfaces, marked by a clast line. At site MT22, in the central part of the Messak, two distinct clast lines mark different topographic surfaces developed in pedogenic phases dating to the early/middle Holocene and the Upper Pleistocene respectively. Relative dating of surfaces is supported by the occurrence of Aterian (Middle Stone Age) artefacts within the lowermost clast line, whereas the uppermost clast line is rich in Pastoral Neolithic artefacts (Cremaschi, 1998; Cancellieri et al., 2016). These topographic surfaces mark the transition between phases of active pedogenesis and human occupation, sustained by climatic conditions wetter than today, and later arid phases of wind accumulation of sediments followed by further pedogenesis (Cremaschi, 1998; Zerboni et al., 2011). This is, for instance, clearly evident at the TK-WS site, where accumulation of parent materials of the uppermost B horizons is well time-constrained to the mid-Holocene transition (Cremaschi et al., 2014).

4.2. Evidence from lithic-strewn surfaces

The main results from the reanalysis of data presented by Foley and Lahr (2015) (Table 2) show that there are fewer lithics counted in each quadrat compared to this previous work, with an average of 45 lithics counted compared to 73 previously. The lithics thus make up a smaller average percentage of total counted clasts within the quadrats (19.7%) than is counted by Foley and Lahr (27.2%). These results are also fairly consistent between different quadrats (except for quadrat A5.5 which has fewer clasts in total and which is dominated by large clasts; see supplementary data file). There are three possible reasons for these differences in lithic counts. (1) Examining digital photos rather than quadrats observed in the field can lead to misidentification, especially of small clasts that are not well-resolved digitally. This may mean that, in this study, the morphology of smaller clasts and flakes may have been misinterpreted and thus the number of lithics may be underestimated. (2) Shaping of lithics and the production of débitage dramatically increases the number of small clasts recorded. This can lead to underestimation from digital images. (3) Clast surface features that can be used to identify the genetic origin of clasts are clearest on the largest clasts (here, < 32 cm diameter) and least clear on the smaller clasts. The planar and intersecting clast surfaces often used to identify lithics, irrespective of their size, can also form as a result of wind abrasion. We suggest that this is the case here, and that many ventifacts or clasts produced by thermal weathering (thermoclastism) have been misinterpreted as lithics. This is discussed in section 5.2.

Table 3 shows that around 40–50% of all clasts show evidence for wind abrasion, forming ventifacts and/or polish. Those clasts discussed by Foley and Lahr (2015) (shown in supplementary data file) can be compared precisely to examples previously recovered from this region (Fig. 4). In addition, 15–20% of all clasts recorded by Foley and Lahr (2015) are actually fractured, having been affected by thermoclastism. Around 30% of all clasts were either too small or too poorly resolved on the digital images to be assigned a genetic origin, or had been substantially affected by other weathering processes, resulting in rounded clasts surfaces with a knobbly, uneven texture. Some clasts (around 15% of the total) show several different morphological features. The most common combinations are ventifacts and polish (Table 4), because they have the same genetic origins, but fractures, ventifacts and polish have also affected 131 individual lithics (some 25% of the total number of lithics recorded). This shows that, irrespective of the total number of lithics, surface weathering processes are very significant in shaping lithic morphologies, most likely after their period of knapping, and following exposure on the land surface possibly for long time periods.

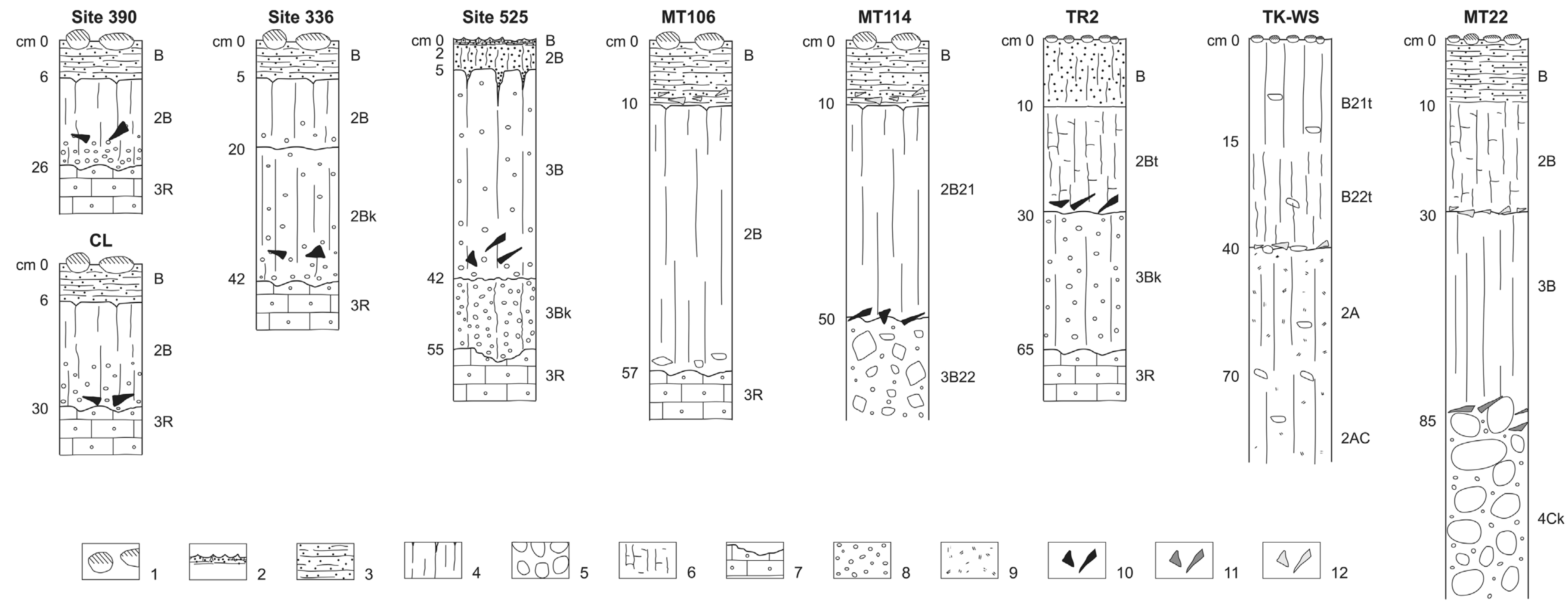

Fig. 3. Examples of pedosequences from the Messak plateau and the nearby Tadrart Acacus massif (sequences TK-WS and TR2 only). Key to stratigraphic features: (1) Dark varnished stones (hamada/serir); (2) cracked sandy–silty crust; (3) laminated sand; (4) rubified B horizon; (5) gravel; (6) rubified B horizon with evident aggregates; (7) sandstone bedrock; (8) $CaCO_3$ nodules and cement; (9) organic matter-rich horizon; (10) Palaeolithic artefacts (Early Stone Age or Middle Stone Age); (11) Palaeolithic artefacts (Aterian); (12) Pastoral Neolithic artefacts.

Table 1
Synthesis of field characteristics of the B horizons described for the considered pedosequences (Fig. 3).

Site (Fig. 3)	Total soil thickness (cm)	Extant desert pavement	Pedosedimentary levels	B horizon thickness	Colour*	Textural class	Rock fragments	Crystalline pedofeatures	Soil structure	Voids	Artefacts**
Site 390	> 30	Granules to pebbles	B	0–8	2.5YR 6/4	Sandy	–	–	Platy, weakly developed	Common, fine vesicular voids	–
			2B	8–30	2.5YR 5/6	Loamy sand	–	Few carbonate concretions	Blocky subangular, strongly developed	Common, fine to medium vesicular voids and vugs	Paleolithic (Middle Stone Age)
Site 525	> 55	Sand	B	0–2	2.5YR 6/4	Loamy sand	–	–	Platy, weakly developed	Common, fine vesicular voids	–
			2B	2–10	2.5YR 5/6	Sand	–	Common carbonate concretions	Blocky subangular, well developed	Common, fine vesicular voids	–
			3B	10–42	2.5YR 5/8	Silt loam	Common, small stones	Few carbonate concretions	Blocky subangular, well developed	Few, fine vesicular voids	Paleolithic
			3Bk	42–55	2.5YR 4/8	Sandy loam	Common, small stones	Common carbonate concretions	Blocky subangular, strongly developed	Few, fine vesicular voids	–
Site 336	> 45	Granules to pebbles	B	0–5	5YR 6/8	Sandy	–	–	Platy, weakly developed	Common, fine vesicular voids	–
			2B	5–20	2,5YR 6/8	–			Blocky subangular, moderately developed		
			2Bk	20–42	2,5YR 6/8	Sandy	Scarce small stones		Blocky subangular, strongly developed		
CL	> 30	Pebbles	B	0–6	2.5YR 6/4	Sandy	–	–	Platy, weakly developed	Common, fine vesicular voids	–
			2B	6–30	2.5YR 5/8	Sandy	Common, small stones		Blocky subangular, strongly developed		
MT106	> 60	Granules	B	0–10	7.5YR 6/4	Sandy	–	–	Platy, weakly developed	Scarce vesicular voids	Pastoral Neolithic
			2B	10–57	2.5YR 5/6	–	Few stones		Blocky subangular, moderately developed		
MT114	> 70	Granules	B	0–10	7.5YR 6/4	Sandy	–	–	Platy, weakly developed	Scarce vesicular voids	Pastoral Neolithic
			2B21	10–50	2.5YR 4/6	–			Prismatic moderately developed		
			3B22	> 50	10R 4/6	Silty sand clay	Few stones	–	Blocky subangular, moderately developed	Very few vesicular voids	–
MT22	> 100	Granules	B	0–10	7.5YR 6/4	Sandy	–	–	Platy, weakly developed	Scarce vesicular voids	–
			2B	10–30	7.5YR 6/4	Sandy	Few stones	–	Blocky subangular, weakly developed	Few, fine vesicular voids	Pastoral Neolithic
			3B	30–85	7.5YR 5/4	Sandy	Few stones	–	Blocky subangular, weakly developed	Few, fine vesicular voids	Paleolithic (Aterian, Middle Stone Age)
			4Ck	> 85	7.5YR 5/4	Gravel with sand matrix	Few stones	Common carbonate concretions	–	Common voids	–
MT22	> 100	Granules	B	0–10	7.5YR 6/4	Sandy	–	–	Platy, weakly developed	Scarce vesicular voids	–
			2B	10–30	7.5YR 6/4	Sandy	Few stones	–	Blocky subangular, weakly developed	Few, fine vesicular voids	Pastoral Neolithic
			3B	30–85	7.5YR 5/4	Sandy	Few stones	–	Blocky subangular, weakly developed	Few, fine vesicular voids	Paleolithic (Aterian, Middle Stone Age)
			4Ck	> 85	7.5YR 5/4	Gravel with sand matrix	Few stones	Common carbonate concretions	–	Common voids	–
TR2	> 60	Granules to pebbles	B	0–10	7.5YR 6/4	Sandy	–	–	Blocky subangular, very weakly developed	Scarce vesicular voids	–
			2Bt	10–30	2.5YR 5/6	Sandy silt loam	Few stones	–	Blocky subangular, moderately developed	Few, fine vesicular voids	Paleolithic
			3Bk	30–65	2.5YR 5/6	Sandy silt loam	–	Frequent carbonate concretions	Blocky subangular, strongly developed	Few, fine vesicular voids	–
TK-WS	> 80	Granules to pebbles	B21t	0–15	7.5YR 7/6	Sandy	Few stones	–	Blocky subangular, weakly developed	Scarce vesicular voids	–

(continued on next page)

Table 1 (*continued*)

Site (Fig. 3)	Total soil thickness (cm)	Extant desert pavement	Pedosedimentary levels	B horizon thickness	Colour*	Textural class	Rock fragments	Crystalline pedofeatures	Soil structure	Voids	Artefacts**
			B22t	15–40	10YR 5/4	–	Few stones		Blocky subangular, weakly developed		
			2A	40–70	10YR 4/2	–	Rare to common stones		Blocky subangular to platy, weakly developed		
			2AC	> 70	2.5YR 5/2	–	Few stones		Massive		

*Colour according the Munsell Color Chart.
**Most dominant artefact assemblage found.

Table 2
Calculated numbers of clasts within sample quadrats (defined by Foley and Lahr, 2015) that can be classified as lithics (stone tools), according to Foley and Lahr (2015) and this study.

Quadrat #	Foley and Lahr, 2015			This study		
	Total # clasts	Total # lithics	% lithics	Total # clasts	Total # lithics	% lithics
A1.1	147	91	62.0	222	31	14.0
A1.5	320	66	20.6	224	38	16.9
A1.8	186	73	39.2	233	45	19.3
A2.3	387	96	24.8	247	52	21.0
A2.5	219	67	30.6	230	40	17.4
A3.2	357	89	24.9	254	51	20.0
A3.7	482	73	15.1	237	53	22.3
A4.2	261	80	30.6	238	51	21.4
A4.6	314	68	21.6	202	48	23.8
A5.1	206	64	31.0	245	56	22.8
A5.5	116	53	45.7	107	8	7.5
A5.10	218	54	24.7	218	38	17.4
Average	**268**	**73**	**27.2**	**221**	**43**	**19.2**

5. Discussion

5.1. Formation of the desert pavement and palaeosol pedostratigraphies

According to general models (e.g., Busche, 2010; Busche and Sponholz, 1992; Perego et al., 2011), the onset of pedoclimatic conditions that controlled deep bedrock weathering in the central Sahara is dated to the Paleogene. During this phase, sandstone of the Messak Formation was affected by deep weathering under a tropical climate. After a prolonged phase of intense pedogenesis, uplift of the Messak plateau and other massifs around the Murzuq Basin during the Paleogene and Oligocene led to the incision of wadis and progressive removal of the original soil cover by enhanced surface erosion. Only very limited strips of lateritic paleosols (*sensu* Aleva, 1994) have been preserved in the region from this period (Rognon, 1980; Trombino, 1998) and in the Messak such evidence is extremely rare.

Soil-forming processes on the Messak plateau were intermittently active in response to Quaternary wet (interglacial) and dry (glacial) cycles (Trombino, 1998; Zerboni et al., 2011). Greater moisture availability during interglacial periods encouraged bedrock weathering, release of loose sediments to the land surface, the formation of soil horizons relatively enriched in clay, iron oxides-hydroxides, and $CaCO_3$-bearing pedofeatures and pedoplasmation that correspond to physical and chemical processes taking place within the profile in response to climatic variability (Table 1). Underlying weathered bedrock surfaces acted as barriers above which carbonate nodules formed, indicative of CO_2 degassing within the profile. By contrast, during arid/glacial phases pedogenesis was largely interrupted and cyclic episodes of surface deflation, flash flood erosion and dust accumulation occurred. Net surface erosion led to reduction of surface relief and the exposure of residual clasts that have not been fully broken down by weathering. Aeolian dust accumulated on deflated surfaces, being trapped by coarser rock fragments, but the spatial and temporal patterns of this accumulation is not well known. Dust accumulation, representing a mechanism of rapid clast burial, can lead to the formation of clast layers found within pedostratigraphies in the field (Fig. 3). Decreased dust accumulation rates during subsequent wet phases allowed for development of a soil horizon at the surface, and associated pedogenic processes taking place with depth below the surface. Soil forming processes during the Quaternary led to the formation of paleosols that show less intense weathering when compared with those of pre-Quaternary age (Trombino, 1998; Zerboni et al., 2011). This is likely due to less humid climatic conditions in Pleistocene interglacials than in the Neogene, and possibly also to shorter periods of pedogenic activity during the interglacials (e.g., Szabo et al., 1995; Smith et al., 2004; Brookes, 2010;

Table 3
Calculated numbers of clasts within sample quadrats (defined by Foley and Lahr, 2015) that show particular surface geomorphic characteristics. *This total does not double-count clasts that show both ventifacts and polish.

Quadrat #	This study	Clasts showing wind abrasion features (this study)			Clasts showing primary fractures resulting from thermal weathering (this study)		Number of clasts showing no distinguishing characteristics		Number of clasts showing two features	
	Total # clasts	# ventifacts	# polish	% of total*	# clasts	% of total	# clasts	% of total	# clasts	% of total
A1.1	222	64	60	49.0	51	23.0	71	32.0	52	23.4
A1.5	225	66	45	42.7	42	18.6	69	30.7	35	15.5
A1.8	233	61	53	44.6	32	13.7	69	29.6	28	12.0
A2.3	247	67	57	47.8	34	13.8	59	23.9	21	8.5
A2.5	230	72	56	50.8	40	17.4	62	27.0	40	17.4
A3.2	254	72	44	42.1	45	17.7	75	29.5	33	13.0
A3.7	237	60	48	42.6	38	16.0	74	31.2	36	15.2
A4.2	238	52	36	35.3	54	22.7	75	31.5	30	12.6
A4.6	202	41	47	40.0	48	23.8	52	25.7	34	16.8
A5.1	245	48	68	40.8	49	20.0	68	27.7	45	18.4
A5.5	107	24	22	38.3	12	11.2	49	45.8	8	7.5
A5.10	218	66	56	48.6	35	16.0	64	29.3	39	17.9
Average	**221**	**58**	**49**	**43.5**	**40**	**17.8**	**66**	**30.3**	**33**	**14.8**

Fig. 4. Some examples of ventifacts collected by A. Desio in the Libyan central Sahara in the 1930s (in the collections of Università degli Studi di Milano, see Desio, 1937). Note the occurrence of intense wind abrasion producing polished, planar to curved surfaces.

Table 4
Counts of the number of clasts showing different combinations of two surface features.

	Fractures	Polish	Ventifacts
Stone tools	53	23	55
Ventifacts	59	116	
Polish	92		

Zerboni et al., 2011).

The formation of an armoured surface on the Messak is therefore related to multiple surface (and subsurface chemical) processes rather than the single process of deflation, as recently suggested (e.g., Goudie, 2013) (Fig. 5). Cycles of surface erosion, dust accumulation, and pedogenesis occurred several times and contributed to the formation of overlapping soil B horizons and a topsoil corresponding to the desert pavement (Figs. 2 and 5). It also permitted the formation of continuously-refreshed topographic surfaces settled by prehistoric human groups. The latter left lithic scatters on the topsoil surface, which then underwent taphonomic changes associated with surface winnowing or burial to become part of the soil skeleton.

The evolution of the desert pavement observed on the Messak plateau, as described here, is thus analogous to the processes described for other hot deserts (e.g., Springer, 1958; Wells et al., 1995; McFadden et al., 1998; Matmon et al., 2009; Amit et al., 2011; Fujioka and Chappell, 2011; Dietze et al., 2011; Dietze and Kleber, 2012; Fuchs et al., 2015), with similar final products including alternating layers of polished/varnished clasts, a layer of aeolian sandy silt with a vesicular structure (few cm thick), and a deeper, partially weathered soil B horizon (B or Bk or Bt). On the Messak plateau, this sequence may be repeated more than once (Cremaschi, 1998) (Fig. 5), suggesting the existence at some localities of complex pedosequences with preserved buried desert pavements (e.g., Amit and Gerson, 1986; McFadden et al., 1986). Fig. 5 illustrates how buried paleosols and lithic layers may be preserved or condensed over time, depending on the net erosion or deposition on the land surface.

The stratigraphy recorded in buried paleosol sequences from the Messak plateau is similar to those of the Negev and Mojave deserts (Wells et al., 1995; Matmon et al., 2009; Fuchs et al., 2015), where radiometric dating shows desert pavement and soil development over long time periods. In the Messak where there is a lack of direct dating of buried topographic surfaces, some chronological control is provided by buried clast layers that include abundant lithic assemblages corresponding to the Middle and Late Pleistocene periods. However, the condensation of these pedostratigraphies by land surface erosion, mixing lithic assemblages of different ages, means that they cannot be used with confidence as chronostratigraphic marker horizons (e.g., Fanning and Holdaway, 2001), and instead suggest episodic phases of sediment reworking and pedogenesis. Development of the desert pavement also occurred locally during the Mid-Late Holocene arid phase, as confirmed by the occurrence of Pastoral Neolithic lithics buried at some localities (Cremaschi, 1998), and by other evidence for desert pavement formation on renewed surfaces in the region (Cremaschi et al., 2014). This viewpoint is also supported by regional stratigraphic correlations and radiometric dating evidence. For example, two pedogenic concretions at the top of a red paleosol at the western margin of the Messak are assigned to Marine Isotope Stage (MIS) 4 and MIS 7, respectively, suggesting pedogenetic phases at these times (Cancellieri et al., 2016). Regional correlations of Pleistocene limnites in the Murzuq/el-Ajal/Shati areas, east of the Messak (Gaven, 1982; Armitage et al., 2007; Drake et al., 2008; Geyh and Thiedig, 2008), remain the only data so far available to compare with radiometrically-dated phases of pedogenesis that span the Middle-Late Pleistocene (see Cancellieri et al., 2016; for a review). Our evidence suggests that lithic assemblages in the Messak may be used as dating tools for surface and buried desert

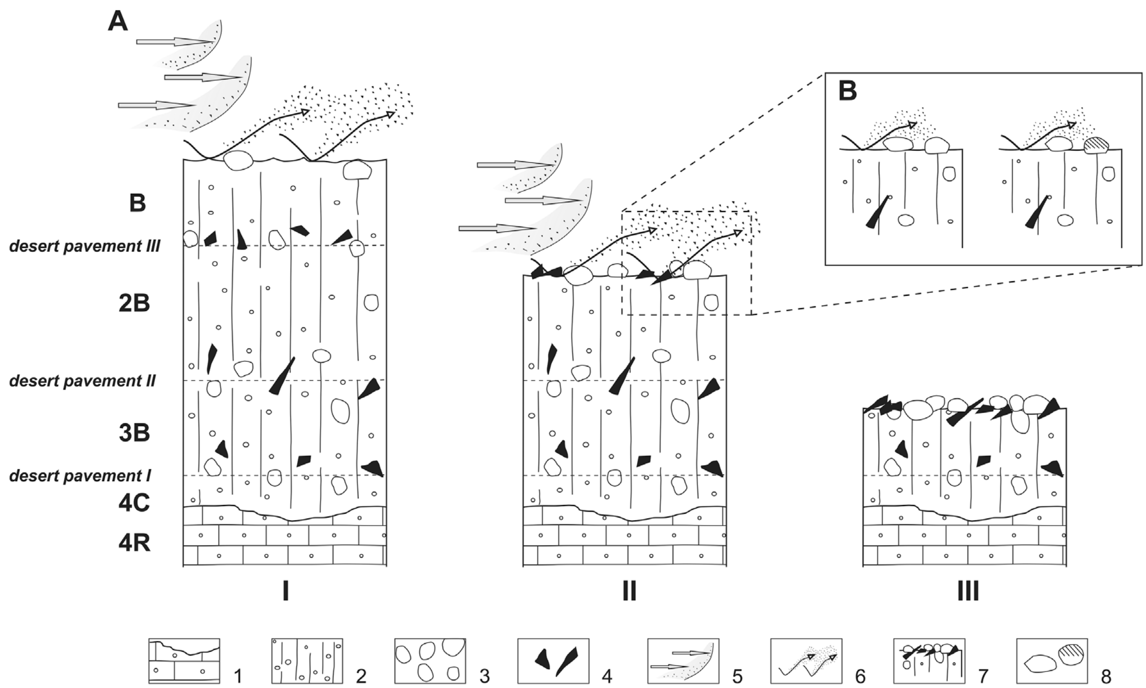

Fig. 5. Schematic model (not to scale) illustrating (A) formation of desert pavements in the central Sahara as a consequence of intense phases of wind deflation, and (B) formation of ventifacts and weathering surfaces on surficial sandstone clasts. Progressively, deflation causes the concentration of clasts of all types on the land surface. Key: (1) sandstone bedrock; (2) loose and weathered sediments, including regolith and palaeosols (if present); (3) residual boulders within the weathered sediments; (4) lithics within the weathered sediments; (5) wind direction; (6) deflation; (7) desert pavement; (8) ventifacts and weathering surface on sandstone blocks (rock varnish).

pavements in the case of *in situ* diagnostic lithics without evidence of transportation. Mixed assemblages cannot be used unequivocally in this way. This method should ideally be used in combination with luminescence and cosmogenic dating, but permits an interpretation of the age of surface and buried landscapes of desert regions. The relationship between surface processes and the fate of lithics in the formation of the local landscape has a clear consequence for the interpretation of lithic-strewn desert surfaces.

5.2. Re-examination of evidence for lithics

The results of the lithics reanalysis show that there are fewer lithics than previously identified, and that a high proportion of clasts show evidence for wind abrasion and subaerial weathering (e.g., Soleilhavoup, 2011). This is consistent with field patterns (e.g., Figs. 2 and 4) and strongly suggests that many wind abrasion forms have been previously misinterpreted as lithics. Clast fracturing as a result of thermal weathering is also significant, because this process can give rise to clasts with planar surfaces and sharp edges that look similar to those that have been knapped. Clasts that have been wind abraded or which are lithics may also be fractured (Table 4). Although the relative timing of formation of the different surface features cannot be established in most cases, the presence of these features suggests that the clasts experienced several episodes of morphological development, either before or after fracturing, and which supports arguments that bedrock uplands of the central Sahara represent old land surfaces that have experienced different phases of evolution and under somewhat different climatic regimes (Zerboni, 2008; Adelsberger and Smith, 2009).

Foley and Lahr (2015) used their counts of lithic density and assumptions of lithic age and human population structure to calculate lithic number and total knapped volume across the wider central Sahara region. The problem with such calculations is that the assumptions are often not well founded and subject to high error and that, in this case, counts of lithic density in the field quadrats appear to be around 70% higher than in the reanalysis (see Table 2). This casts doubt on the validity of such calculations and the inferences made from them. The effects of wind abrasion have been noted across the central Sahara (e.g., Brookes, 2003; Cigolini et al., 2012), and wind abrasion (and possibly with other types of weathering) may have modified pre-existing surface lithics or helped shape clasts that may be then misinterpreted as lithics. This is consistent with several studies elsewhere in which lithics have been modified post-formation (e.g., Lancaster, 1986; Burroni et al., 2002; Ugelde et al., 2015; Borrazzo, 2016). In addition, desert regions are known to the characterised by high rates of sand transport, resulting in a range of wind erosion features (Goudie, 1989).

5.3. Spatial patterns of lithics

Foley and Lahr (2015) argued that clustering of lithics on the land surface reflects primary patterns of human activity (i.e., that the lithics are *in situ*), and does not reflect natural geomorphological processes. This is suggested to be the case over regional-scale landscapes (Fanning and Holdaway, 2001). However, wind deflation and overland flow from flash floods are important on a regional scale in surface erosion and sediment transport, forming sand dunes, hamadas, serir, yardangs, slope deposits and alluvial fans (Wright, 2001; Brookes, 2003; Perego et al., 2011; Soleilhavoup, 2011). At a local scale, lightning and bioturbation are also important geomorphic processes (Cigolini et al., 2012; Adelsberger et al., 2013; Haff, 2014), and can affect the preferential preservation on the land surface of smaller rather than larger lithics (Adelsberger et al., 2013). At the very localised scale of 1 × 1 m quadrats, any clustering of surface lithics can be the result of two components in combination: (1) anthropogenic production of lithics over long time scales, accumulating progressively and thus increasing in density on the land surface, and (2) physical weathering and erosion processes operating on the land surface and concentrating both lithics and non-anthropogenic clasts over time, and by episodic bioturbation. It is this latter set of processes that can better account for clusters of lithics on the land surface. Increased lithic density can be caused by progressive deflation of surrounding fine sediments, or by washing clasts into depressions during flash floods (Williams and Zimbelman, 1994; Dietze et al., 2013). In the case of the Messak plateau surface,

both lithics and natural weathered clasts may have been exhumed from within paleosols and buried desert pavements by aeolian deflation (and rarely by fluvial erosion) (Fig. 5); these erosional events are known to have occurred several times from the Middle Pleistocene onwards (Perego et al., 2011), and to have contributed to the formation of desert pavements (Zerboni, 2008). As an example, the Messak surface shows a palimpsest of lithic scatters, which range in age from the Middle and Late Acheulean up to historical times (Cremaschi and di Lernia, 2000; di Lernia, 2006). It is likely that this comes about through progressive land surface erosion, resulting in a condensed residual lag that contains lithics (and clasts) of a range of ages (Fig. 5). Lithics that are found buried within soil pedosequences are also of mixed ages, indicating alternate phases of sediment stripping by net erosion during which mixed-age assemblages accumulate, and burial by net sediment accumulation which preserves these assemblages. This fits with the (albeit limited) cosmogenic dates available from desert regions that show that these are old landscapes that have experienced several climatically-controlled weathering and erosional phases (e.g., Matmon et al., 2009; Fujioka and Chappell, 2011). An alternative viewpoint of multiple occupations of a single site on a stable land surface can indeed account for a range of lithic ages being present (Foley and Lahr, 2015), but this cannot account for variable preservation of lithic or how they have been modified post-formation by weathering and abrasion (Table 3). Further, several studies in the wider Saharan region show that physical processes have a significant impact on lithic spatial patterns and properties (Adelsberger et al., 2013; Koopman et al., 2016). Several predictive models have also been developed in order to better understand these relationships (Fanning and Holdaway, 2001; Barton and Riel-Salvatore, 2014; Davies et al., 2016). Previous studies have shown that the highest concentrations of lithics are located in the vicinity of sandstone outcrops, which were exploited for several thousands of years, from the Palaeolithic to the Pastoral Neolithic phases (Cremaschi and di Lernia, 2000; di Lernia et al., 2013). Moreover, as discussed above, bedrock outcrops exposed today upslope of wadis likely correspond to areas where erosion was more intense in the past, thus removing almost the whole sedimentary cover and washing materials into paleo-lows on the land surface. The very limited spatial scale of this process (commonly a few m) means that lithics (and other clasts) experienced very limited or no abrasion during transport. Prolonged human occupation of the area resulted in a high quantity of artefacts including stone tools and débitage, but their extant positions in the landscape on summit or gently sloping surfaces rather than within wadi channels suggest that physical processes of wind erosion were most significant, which removed the pedological cover and concentrated both clasts and lithics. Surface lithic concentration cannot therefore be used in an interpretive sense to say anything about the density of human occupation or its imprints on the landscape, but merely to suggest subsequent phases of human exploitation in that area.

5.4. Implications for the evolution of land surfaces and the archaeological record in desert regions

Interrelationships between land surface processes and formation of the archaeological record in desert regions are only now starting to be examined in detail from taphonomic (e.g., Borrazzo, 2016; Leonardt et al., 2016; O'Neal and Lowery, 2017), modelling (e.g., Barton and Riel-Salvatore, 2014; Davies et al., 2016), and environmental perspectives (e.g., Cancellieri and di Lernia, 2013; Ugalde et al., 2015; Koopman et al., 2016), but there are lots of gaps in our understanding. These include the evolution of hamada and serir surfaces and implications for clast and lithic movement upon these surfaces (Fanning and Holdaway, 2001; Adelsberger et al., 2013), and the significance and interpretation of lithic scatters. This study uses two independent lines of evidence to show that a geomorphological understanding of the properties and development of the land surface (pedostratigraphic levels) can yield a better interpretation of composite surface lithic scatters (recalculation of Foley and Lahr's (2015) data).

The study by Foley and Lahr (2015) argued that the Messak plateau is an anthropogenic landscape due to its high density of lithics that provide evidence for intensive human activity over a long time period. However, the reanalysis of their data undertaken in this present study (Tables 2–4) shows that their conclusions are not well founded. The Messak plateau shows evidence of intense human activity over a long time period, but geomorphological processes including wind action – forming ventifacts (e.g., Fig. 4) – are the most significant controls on land surface features, including development of the condensed pedostratigraphy that today's land surface represents. This is clearly reflected in the erosional and aggradational phases in the soil pedostratigraphies from this region (Figs. 3 and 5), which are not spatially uniform across the landscape, and which relate to both aeolian and episodic fluvial processes in combination. The Messak plateau varies from areas where some elements of the ancient desert pavement are preserved by burial beneath the extant one, to areas where a thin layer of desert pavement (hamada or serir) is present, to other areas where bare sandstone outcrops are present with no desert pavement existing (Perego et al., 2011). The higher preservation by burial of paleosols on the southern side of the plateau in depressions or inter-wadi areas reflects sediment removal and redistribution by erosion, and thus selective preservation on the land surface of both ventifacts and lithics, originally corresponding to different phases of the Quaternary. This evidence shows that desert surfaces should be viewed as condensed palimpsests (e.g., Bailey, 2007; Davies et al., 2016), which vary over time and space, and that lithic scatters are the product of progressive land surface erosion. The viewpoint that surface lithic scatters in the central Sahara reflect human activity over long time periods – the so-called 'Palaeoanthropocene' (Foley et al., 2013) – is an uncritical interpretation of this lithic evidence without considering the significant role of geomorphological processes in changing the spatial patterns and morphologies of any surface clasts.

6. Conclusions

Evidence from soil pedostratigraphies and reinterpretation of published data on surface lithic scatters sheds new light on the development of desert surfaces in the Messak plateau. The condensed soil pedostratigraphies provide evidence for multiple accumulation and deflation events during the Quaternary, which have contributed to the mixing of clasts/lithics on the land surface, which have, in some cases, been then buried by later aeolian sediment deposition. This is a similar mechanism allowing for the preservation of paleosols. In addition to this mixing of lithics of different ages, surface lithics show substantial evidence for alteration by aeolian processes, forming ventifacts (Fig. 2). This is in contrast to the study by Foley and Lahr (2015) that does not identify such evidence. As such, the evidence for high-density lithic scatters is not as clear as has been previously reported, and that extrapolating lithic densities in sample quadrats to the regional scale of the Messak plateau is inappropriate, because it results in inaccurate interpretations of the significance of human occupation in the area over the last 500,000 years. The interpretation of palimpsest lithic landscapes should also be undertaken on the basis of a regional approach, or considering distinct geomorphological units (as done by Cancellieri and di Lernia (2013) and Cancellieri et al. (2016) in the case of the Messak plateau), rather than generalizing across wide landscapes from only a small study area.

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Appendix A. Supplementary data

Reanalysis of the quadrat data presented by Foley and Lahr (2015). Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jaridenv.2018.01.007.

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